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EXPERIMENTAL INVESTIGATION OF THE CONSTANT-VOLUME PULSED ROCKET CONCEPT (PREPRINT)

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ABSTRACT

Constant-volume combustion pulsed rocket systems may offer significant operational advantages over traditional constant-pressure rocket systems, including the reduced weight and complexity of low pressure propellant feed systems. A novel sub-scale facility has been built and tested at AFRL to assess the merits and feasibility of a constant-volume pulsed combustion rocket motor. Initial hotfire testing has been performed and those results are compared with a simple transient numerical model to assess performance. In initial testing with nitromethane based monopropellants, little modulation in chamber pressure has been achieved. Some substantial chamber pressure modulation has been achieved in partially pulsed bi-propellant operation, but this behavior is still significantly below ideal levels. Further modification of test hardware and use of more volatile monopropellants may enable a more operable cycle.

INTRODUCTION

A constant-volume combustion cycle may offer a number of operational advantages when compared with a traditional constant-pressure rocket propulsion system. Injecting the propellants at a pressure lower than the average chamber pressure reduces the weight and complexity of propellant feed systems and lowers costs. Conversely, moving to a constant-volume cycle allows increased performance to be obtained from an existing propellant feed system. This paper presents the development and initial testing of a small-scale constant-volume pulsed combustor system to allow exploration of the utility and feasibility of the non-detonative pulsed rocket combustor concept.

BACKGROUND

Propulsion devices utilizing pulsating combustion have been investigated since the early days of jet propulsion. The history of these concepts has been documented through searches of patent records and published literature and reviews are available[1,2]. There has been a rebirth of interest in pulsed propulsion over the last ten years with the seeds coming from a study of the Pulse Detonation Engine (PDE) concept by Helman, Shreeve and Eidelman[3] in 1986 at the Naval Post Graduate School. Eidelman continued to pursue the PDE concept through the 1990s, serving as the leading proponent at conferences, winning a series of research contracts, and publishing a number of articles detailing progress on experimental and analytical issues[4,5]. The concept was also picked up and developed by Bussing at Adroit Systems, Inc. under a series of Air Force SBIR, and Office of Naval Research contracts. The idea caught on and it can now be said that virtually every organization devoted to aerospace propulsion research throughout the world has investigated the concept to some degree. The recent history and developments relevant to air-breathing propulsion have been reviewed by Kailasanath[6] (2004) and Roy et. al.[7] (2004).

Engines operating with pulsating combustion can be grouped into three categories: pulse-jet, constant-volume (also called explosion-cycle), and pulse-detonation. All three types generate a pressure rise directly from the combustion process, thereby reducing or eliminating the need for a compressor or pump and increasing the pressure ratio available for expansion of exhaust gases. In the constant-volume combustion approach, the combustible mixture is introduced into the combustion chamber and then confined and ignited. When the energy release is complete the mixture is exhausted to generate thrust. Confining the combustion event results in a larger pressure rise than that observed in resonant gas-dynamic systems, such as the traditional pulse-jet. In practice this can be accomplished by placing valves in the combustion chamber inlet and exhaust as in the case of the very early Holzwarth turbine[8]. A constant-volume combustion event can be realized without the use of valves if the combustion chamber is large relative to the size of the exhaust nozzle, so that there is ample time for the reaction to complete before an appreciable amount of mass exits the chamber[9]. However, this approach necessarily increases the cycle period. Another approach to constant-volume combustion is to combust the mixture with a detonation wave. A drawback of detonative combustion is that large transient over-pressures occur behind the detonation wave which are

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significantly higher than the effective combustor headwall pressure. These transients require significant margin in hardware design and necessitate a heavier combustion chamber than would be required for a non-detonative pulsed combustor.

Previous work by Coy used a computational model that included finite-rate processes to assess the potential benefits of constant-volume combustion engines for satellite applications[10]. A zero-dimensional model was used for the combustion chamber and a one-dimensional, quasi-steady approximation was used for nozzle flow. The liquid monopropellant spray was assumed to have a log-normal distribution of spherical droplets and the reaction rate was based on a strand burner correlation. The model was developed as a tool for designing an experimental rocket. In the paper it was used to explore the time and dimensional scales of the problem and to predict the performance and optimal geometry. The pulsed propulsion device was found to have nearly identical specific impulse to the steady-state engine operating with the same mass flow and throat area. Furthermore, the nozzle optimized at the same area ratio. Pulsed combustor behavior was shown to depend on three time scales: the heat release time, the chamber blow-down time, and the injector pulsing period. The significance of these scales on performance was shown. In the satellite application study the effect of pulsed combustion devices with pressure-fed propellant systems on satellite mission was examined. It was found that by increasing the average chamber pressure through the use of constant-volume combustion, the area ratio of the nozzle could be increased within the existing space envelope and this would yield an increase in specific impulse of ~6 seconds. The fuel savings were projected to translate into from six months to a year of extended satellite life.

The cycle being investigated here is a small monopropellant fed pulsed combustor. Monopropellants are desirable for the reduced cost and complexity of a single propellant feed system. Nitromethane was selected as a candidate monopropellant for this investigation because of its stability, low cost and ease of handling. Its performance and utility as a monopropellant have been previously investigated by Aerojet, JPL and others with mixed results[11]. Problems were frequently encountered with erratic combustion and poor ignition characteristics. Additives were found to improve utility as a monopropellant with some cost in performance.

MODELING

Prediction of performance and behavior in a pulsed combustor system is complicated by the independently varying transient behavior of many variables. For example, each propellant injection is interacting with the contents of the combustion chamber from the previous cycle, so a variation in the injection repetition rate will have a significant impact on the observed behavior. A simple transient numerical model was developed to allow the investigation of pulsed-combustion cycles and the prediction of optimal experimental performance. This LabVIEW based application steps through time and performs three processes for each time-step: 1) mass addition, 2) equilibrium combustion, and 3) isentropic blowdown through a choked nozzle. The chamber temperature, density and product species' weight fractions at the end of the blowdown are then used as the initial condition for the next time-step. Time varying mass flowrates for any number of propellants are specified for a given combustor volume and nozzle diameter and the model is allowed to march through time. Propellant may be admitted in a steady flow for a period of time or be intermittently pulsed at some frequency. After the mass addition, the NASA-Lewis CEA 600 chemical equilibrium code is used to model the chamber contents coming to thermodynamic equilibrium at constant volume and internal energy. A simple ideal-gas isentropic blowdown model is then used to model the flow of exhaust products out of the chamber through the choked nozzle and determine the resulting change in chamber pressure and temperature.

A number of simulations of nitromethane combustion cycles were performed to investigate the stability and accuracy of the model. Plots of the chamber pressure and c* simulations are shown below in Figure 1 for the steady flow and 50 Hz pulsed calculations. Results from simulations of neat nitromethane combustion for 10, 50 and 100 Hz pulsed combustion and for steady flow, are shown below in Table 1. Results of a standard CEA "rocket problem" analysis for the steady flow case are also listed in Table 1 for comparison. Given the relatively crude nature of the model, agreement is quite good. The chosen metric for comparing the cycle performance is the characteristic velocity (c*) as defined in Equation 1, below, where p is chamber stagnation pressure, A_t is nozzle throat area and *mdot* is the exhaust mass flowrate. Characteristic velocity indicates only the combustion performance of the cycle; a properly designed, and perhaps time-varying nozzle would be required to translate good c* performance into high specific impulse (Isp). No attempt is being made to compare fully developed propulsion systems at this level of fidelity, but simply to explore the potential merit or detriment of the pulsed cycle when compared with a constant-pressure system. The time averaged c* values for the pulsed system are clearly lower than those for the steady system. However, for a transient cycle the time average is an inappropriate metric as time spent at low c* is of little consequence if most of the mass is being expelled during the portions of the cycle where c* is high. A better comparison is made using the mass-averaged c* as defined in Equation 2, below. A higher mass-averaged c* would indicate a better combustion cycle and the potential for obtaining higher Isp. The final column in Table 1 lists the mass averaged c* normalized by the AFRL model steady case result. The pulsed systems are shown to be

equivalent to the steady system for the same propellant flowrate and nozzle throat area, which agrees well with the analysis presented in Coy (2003)[10].

Table 1. Results of simulations comparing steady and pulsed combustion cycles

Propellant	CH_3NO_2	
Avg. Mdot	6.24E-03	**[lbm/s]**
Combustor Volume	0.837	**[in^3]**
Nozzle Throat Dia.	0.094	**[in]**
Time Step	50	**[μs]**

Model	**Pulse Rate**	**Avg. $p_{chamber}$**	**$\Delta p_{chamber}$**	**Avg. c^*_{time}**	**Avg. c^*_{mass}**	**Norm. c^*_{mass}**
	[Hz]	**[psia]**	**[psi]**	**[ft/s]**	**[ft/s]**	**[ ]**
CEA Rocket Prob	Steady	141.3	0	5022	5022	0.99
AFRL Unsteady	Steady	142.8	0	5083	5083	1.00
AFRL Unsteady	10	141.2	3686.9	3029	5026	0.99
AFRL Unsteady	50	142.0	730.8	4457	5054	0.99
AFRL Unsteady	100	142.4	365.0	4867	5070	1.00

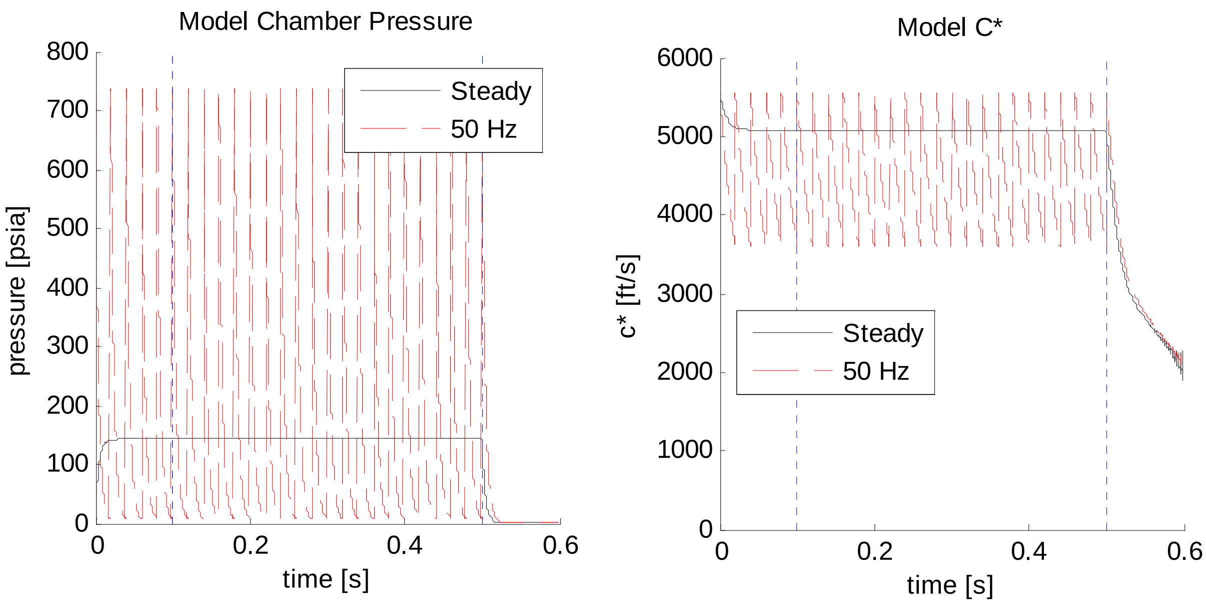


Figure 1. Simulated time traces for nitromethane combustion (6.24 x 10^{-3} lb/s) for both pulsed and steady flow. Propellant flows start at 0 s and end at 0.5 s. Vertical lines indicate period used for analysis in Table 1.

$$c^* \equiv \frac{p A_t}{\dot{m}} \qquad (1)$$

$$\overline{c^*_m} = \frac{\sum_i c^*_i \dot{m}_i \Delta t}{\sum_i \dot{m}_i \Delta t} \qquad (2)$$

EXPERIMENTAL SETUP

The experimental testing was performed in a new facility at AFRL which was constructed for this purpose. A schematic of the facility is shown below in Figure 2. Three separate propellant streams are provided: gaseous hydrogen (GH2), gaseous oxygen (GOX) and liquid monopropellant. Gaseous nitrogen (GN2) is provided for both monopropellant pressurization and purge gas.

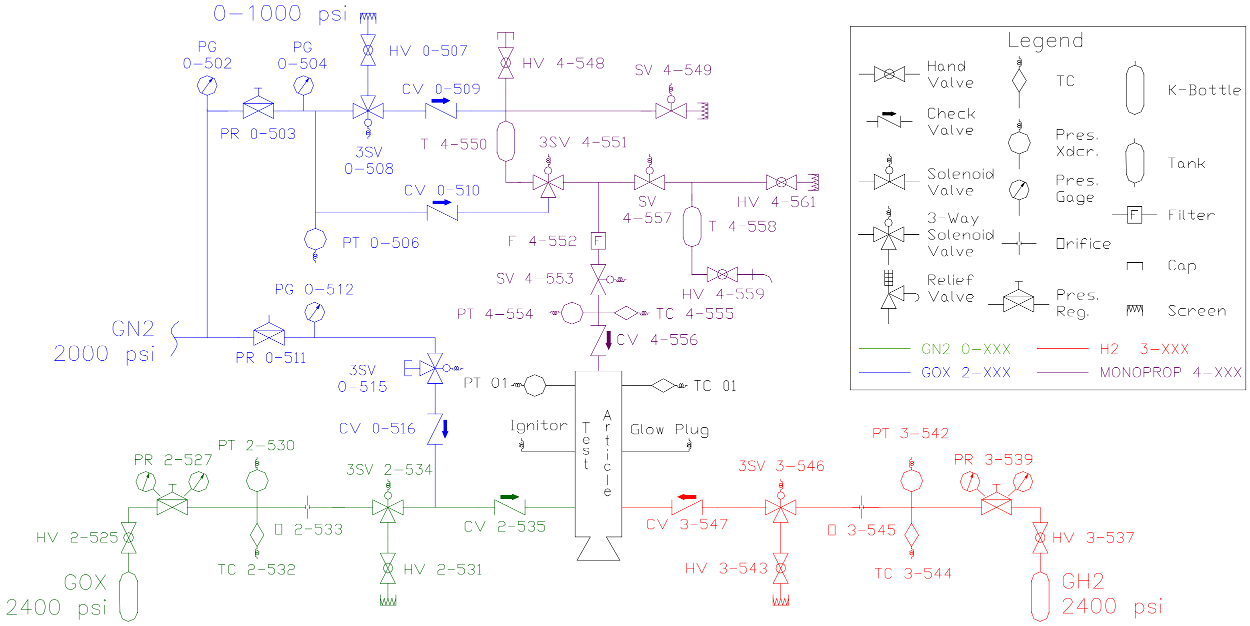


Figure 2. Simplified schematic of the AFRL Pulsed Combustor Rocket Facility.

The test article used in this testing is depicted below in Figure 3. The test article is constructed of three modular 304 stainless steel sections and closed with a copper nozzle. Stainless steel was chosen for its poor thermal conductivity, which results in elevated wall surface temperatures. This hot chamber wall facilitates vaporization of any liquid propellant which impinges on the wall and reduces heat losses. The combustor internal diameter is 0.5" and the length from the injector to the nozzle throat is 4.9" in all of the results presented here. The nozzle used in all of this testing has a throat diameter of 3/32". The combustor sections and nozzle are secured to the combustor top plate by four ¼" stainless steel cap screws that run through the motor sections and the joints between the sections are closed with 0.015" Teflon gaskets. The chamber is equipped with a Kistler 614A piezoelectric pressure transducer to monitor the fluctuating chamber pressure. The transducer is purged with GN2 to keep combustion gas from heating and damaging the sensing element. This purge gas flow is less than one percent of the total chamber mass flow. A type K thermocouple probe located in a thermowell recessed 0.1" from the combustion chamber, is used to observe heat transfer to the wall.

The two gaseous propellant flows are used principally for ignition, but the GOX has also been used as oxidizing augmenter to the fuel rich monopropellant flow. The gaseous propellant flows are metered through choked orifices. These propellants enter the test section through two pairs of 1/16" ports, oriented at right angles to each other. A previous version of this test article used a single pair of opposing GH2 and GOX jets to mix the gaseous propellants, but a large momentum mismatch occurred for very fuel rich mixtures that resulted in impingement of the GOX jet on the chamber walls. The two pairs of like-on-like jets mitigate this issue and still result in adequate mixing.

The monopropellant system is designed to inject liquid propellant into the test article while allowing substantial variation in timing and flowrate. To this end, a high pressure monopropellant system has been implemented which does not take advantage of the merits of the pulse combustor concept (i.e. low propellant feed pressures) but which does produce a very flexible and safe operational system for general research purposes. The monopropellant system is designed to operate on very small quantities of propellant, approximately 3.5 oz, which helps to mitigate the risk of explosion posed by monopropellant systems. The monopropellant is loaded into a 5 oz capacity run tank and pressurized with GN2. The tank pressurization is performed as part of the automated test sequence, a few seconds before the firing, to limit the amount of nitrogen absorbed by the propellant. In previous testing, dissolved nitrogen was found to come out of solution in regions of reduced pressure and form gas pockets which drastically reduce the time response of the liquid injection.

The monopropellant injector was designed for this testing to allow maximum variation in valve timing while rapidly delivering and atomizing the monopropellant. The injection element is a poppet valve extracted from a direct-injection 2-stroke motor, gasoline injector. Atomization is accomplished across the narrow annulus formed when the poppet displaces. The poppet valve requires a large differential pressure of approximately 250 psi to open, and will close when the chamber pressure rises to within 250 psi of the supply pressure. This behavior helps to mitigate the

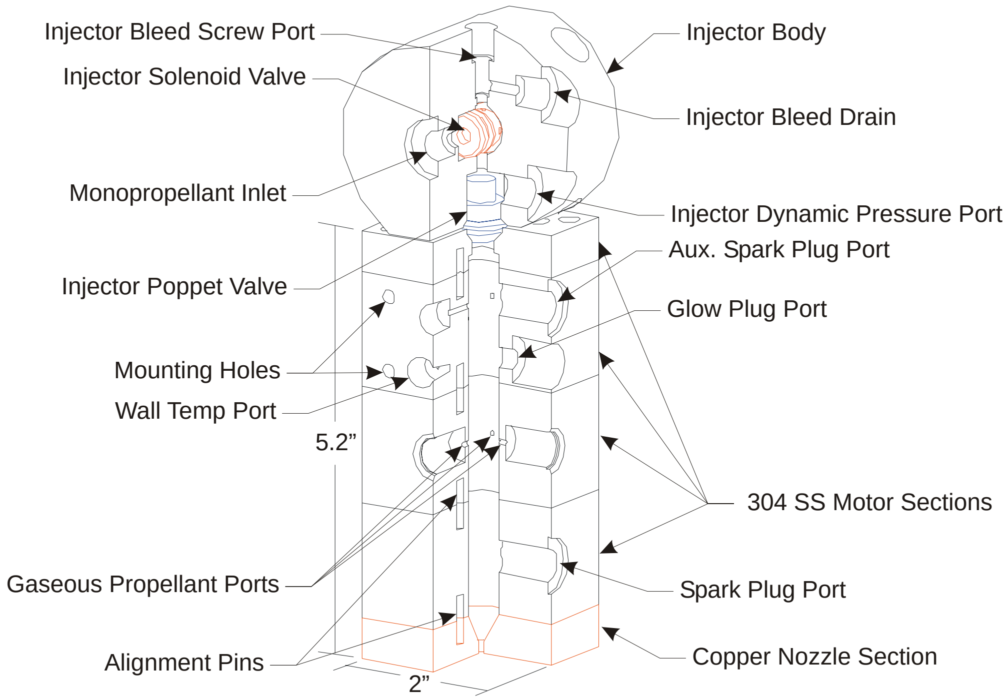
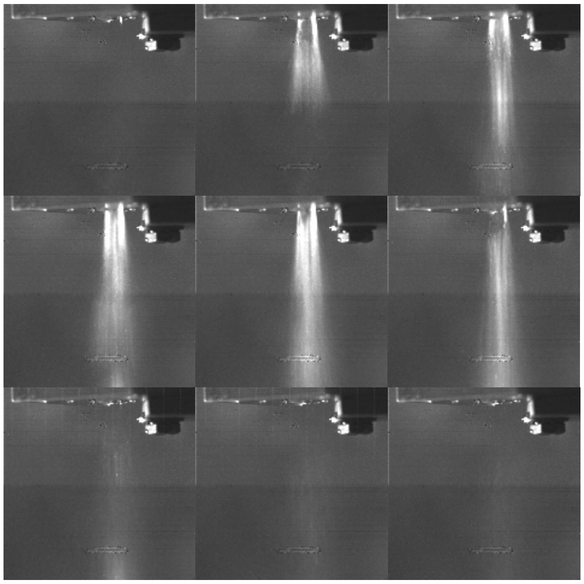


Figure 3. Partial cutaway view of the assembled test article.

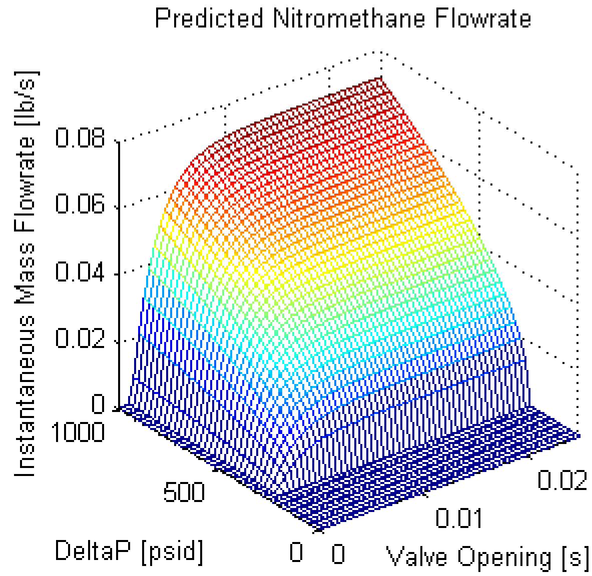
risk of monopropellant flashback. The propellant switching is performed with a Moog 50X824A solenoid valve. The Moog valve was used because of its fast time response and because it was readily available from a previous test program. The valve is limited to a working pressure of 1000 psig and is the mass flowrate limiting factor in the monopropellant feed system. The geometry of the injector body is arranged to minimize the propellant volume between the solenoid and poppet valves in order to minimize the response time of the injector. A bleed valve screw at the top of the injector body allows the elimination of the gas pocket that remains when the fuel is loaded. This is essential to fully hardening the monopropellant system and obtaining the desired injector time response. It also mitigates the risk of adiabatic compression in that gas pocket causing ignition in more sensitive monopropellants when the injector pressure is impulsively increased. A Kistler 603B1 piezoelectric pressure transducer is mounted in the injector body between the solenoid and poppet valves and is used to observe the actual time response of the injector hardware. A type K thermocouple is installed in a thermowell in the injector body to observe the monopropellant temperature inside the injector body. The injector is subjected to heating from the combustion chamber and resistive heating in the solenoid valve, and care must be taken that the injector temperature does not become excessive and induce thermal decomposition of the monopropellant within the injector body.

The transient flow through the monopropellant injector presents particular difficulties for controlling and quantifying the amount of monopropellant injected during each pulse. The injector atomization and time response were observed with no back pressure in the AFRL Flow Lab water flow facility. Part of a typical set of images of a water injection is shown in Figure 4(a). The response time from the valve actuation signal to water leaving the injector was typically 4 ms, and the response from the closing signal to the end of the injection pulse was typically 8 ms. Much of this delay is the time required for the propellant to physically travel, as the injector dynamic pressure typically began to rise within 1.3 ms of the valve actuation signal. Mass flowrate measurements were taken in the same facility at both ambient pressure and elevated back pressure. Time average mass flowrates were measured through a series of catch-and-weigh tests and the effective instantaneous mass flowrate during the injection was determined by dividing the average mass flowrate by the injector duty cycle.

A conventional orifice flow equation is shown below in Equation 3, where ρ is the fluid density, Δp is the differential pressure across the orifice, A is the open area of the orifice and Cd is the discharge coefficient. This injector fit this general behavior, but required a number of modifications to produce a usable mass flowrate function, as shown in Equation 4. Due to the transient nature of pulsed injection, some dependence on the pulsing rate and/or duty cycle was expected. A parametric study of injector behavior found that the most significant effects are governed by the duration of the injection pulse and the injector behavior is generally independent of the pulse rate. For relatively long injections (> 5 ms) the transient effects of the injection pulse are negligible and the average mass flowrate during



(a)



(b)

Figure 4. (a) High-speed images of monopropellant characterization with water. 610 psi feed pressure. 50 Hz injection @ 30% duty cycle. Sidelit images taken at 1 kHz. (b) Expected monopropellant instantaneous mass flowrate function over the expected range of differential pressures and pulse widths.

each injection is dependent only on Δp. For pulses shorter than 5 ms, the transient response of the poppet valve is a significant fraction of the injection duration and the average flowrate over the pulse is reduced. For very small pulses (< 1.25 ms), no injection occurs at all. The differential pressure across the injector must be high enough to overcome the poppet valve crack pressure, so the entire curve is displaced to higher pressures. In addition, at marginal differential pressures, there is some non-linearity in the poppet valve response and an exponential term was added to Equation 4 to correct for this. The plot in Figure 4(b) shows the predicted flowrate of neat nitromethane using Equation 4 and the discharge coefficient determined from the water calibrations.

$$\dot{m} = \mathrm{Cd\,A}\sqrt{2\,\rho\cdot\Delta p} \tag{3}$$

$$\dot{m} = \mathrm{Cd\,A}\sqrt{2\,\rho(\Delta p - 250\text{ psi})}\left(1-\exp\left(\frac{1.25ms - t_{open}}{2.25ms}\right)\right)\left(1-\exp\left(\frac{(250\text{ psi} - \Delta p)}{135\,psi}\right)\right) \tag{4}$$

The true flowrate of liquid propellant remains a significant uncertainty in this program. A secondary variation in flowrate with injection frequency was also observed in the Flow Lab testing. This behavior was generally attributed to coupling with the facility water feed system which was clearly observed to be oscillating. However, some resonance in the feed systems used for pulsed rocket testing is also feasible and deserves further attention. This work assumes that the Reynolds numbers inside the injector are high enough that the discharge coefficient is the same for the water during calibration and the liquid propellants during hotfire testing. Actual calibrations with the fluids in question would help to build confidence in this assumption. The calibrations were performed against a fixed back pressure, but the dynamic back pressure of a pulsed combustion chamber may produce decidedly different results and deserves further consideration. Some exploratory effort has gone into obtaining a time-resolved positive displacement flow meter to obtain a better measurement of the monopropellant flowrate under different modes of operation.

Two means of ignition are provided in the combustion chamber, a traditional spark plug and a glow plug. The spark plug is driven by a Mallory Hyfire IV automotive ignition which was adapted to this work. Typical spark energies are on the order of 100 mJ. Two different spark plugs were used in this work. The first was a Champion G52V surface gap style plug. This style of plug has been used successfully in a number of hotfire applications at AFRL, but was found to function erratically at elevated pressures for very fuel rich hydrogen/oxygen mixtures. Under these conditions the spark system would still discharge, but the discharge was occurring at a location other than the

plug gap, thus resulting in no ignition and significant power discharge through the data acquisition system. Subsequent evaluation of an NGK CR9E traditional J-gap style spark plug demonstrated much more repeatable performance at pressures up to 400 psig. All of the results presented here were obtained using the NGK spark plug. A Thunderbolt R/C Long glowplug was provided as a secondary ignition source. It can be driven externally by a 1.5 V power supply, but is intended as a source of carryover heat from one combustion pulse to the next to act as an initiation source, as it does in traditional small-scale nitromethane fueled reciprocating engines.

Data acquisition and control are performed using a custom LabVIEW application that was written for this test program. The data is acquired with a personal computer (PC) mounted National Instruments PCI-6071E data acquisition card. This is a 64 channel, 12 bit data acquisition card which supports aggregate acquisition rates up to 1.25 megasamples per second. The experimental control is performed by a National Instruments PCI-6534 digital input/output card, which provides 32 channels of digital input or output and is capable of output rates up to 20 MHz. Before each test, the timing for the valves, igniters and relays is calculated by the LabVIEW application and loaded into the 6534 buffer. During the experiment, the digital output card then sequentially steps through the buffer. If the test conductor orders a halt to the test sequence, the buffer output is interrupted and the system is put into a safe default state. The LabVIEW application and the associated data acquisition and digital control functions are performed by a PC that is located in the test cell. That application is in turn controlled remotely using a keyboard, video and mouse (KVM) extender and a terminal located in a remote blockhouse.

A typical test firing is initiated by starting the GH2 and GOX flows, which mix in the combustion chamber. They are ignited by the spark plug and allowed to achieve a nearly steady chamber pressure. The monopropellant is then injected in short repetitive pulses. The monopropellant is ignited by the GH2/GOX torch and rapidly burns, significantly raising the chamber pressure. The chamber pressure then falls as the chamber blows down through the small nozzle port. Before the chamber has blown down completely, another injection of monopropellant occurs. The hot exhaust products of the previous pulse mix with the fresh charge and ignite it, causing another pulse in the chamber pressure, followed by a subsequent blowdown. After the monopropellant pulses are initiated, the igniter flows are terminated and the motor is transitioned to fully pulsed operation.

Testing was performed with nitromethane and a number of blends of nitromethane with methanol and propylene oxide. Methanol was used in early testing as a diluent for the nitromethane while the potential for flashback and propellant breakdown in the injector was investigated. Propylene oxide was added as an oxygen bearing additive and to raise the vapor pressure of the monopropellant mixture to improve atomization.

RESULTS AND DISCUSSION

A number of developmental tests of the Constant-Volume Pulsed Rocket facility have been performed. This testing was used to explore the hardware limitations of the facility, develop operational procedures and techniques and explore what level of combustion chamber pressure modulation could be achieved with this system. Table 2 summarizes some of the developmental testing that was performed. The Torch parameters indicate the measured chamber pressure and the equivalence ratio of the igniter torch gases just before the liquid propellant began to pulse into the combustion chamber. The Pulsed Propellant parameters list the injection rate, injector duty cycle and an estimate of the average mass injected during each pulse. Finally, the Typical Pressure Modulation columns list the measured differential pressures observed in the tests. Three different differential pressures are listed. Δp is the pressure modulation when both the GOX and GH2 flows have been stopped and the liquid is acting as a monopropellant. Δp w/ Torch is the pressure modulation which occurred when the liquid propellant is injected into the full torch flow, which typically occurs at the beginning of the pulsed phase of the test. Δp w/ GOX is the pressure modulation which occurred when the liquid propellant is injected into just the GOX flow and the system is functioning as a partially pulsed bi-propellant system; this approach was found to be the most effective in achieving appreciable chamber pressure modulation. The reported differential pressures are typical values pulled off of the chamber pressure plots. A blank cell indicates that type of operation did not occur in the test under consideration, while a zero value indicates that phase of operation did occur but no modulation was observed.

Testing began with water (H_2O) serving as a safe stand in for a monopropellant. Some pressure modulation was observed in this testing simply due to vaporization of the water. With all monopropellant systems, there is a significant risk of combustion flashing into the feed system, so tests were performed with neat methanol (CH_3OH) to assess the heat transfer to the injector during pulsed injection of a combusting liquid. A limited number of tests with excess GOX demonstrated that some significant pressure modulation could be achieved by pulsing only the fuel, but combustion was erratic and uneven. Testing then progressed through a series of mixtures of nitromethane (CH_3NO) and methanol of gradually increasing strength. Testing was then performed with neat nitromethane and finally with a mixture of nitromethane and 10% propylene oxide (C_3H_6O). These tests were performed to explore the capability of the test stand and involved considerable troubleshooting to address problems with the new facility. Thus operating

Table 2. Summary of results from developmental testing.

		Torch		Pulsed Propellant			Typical Pressure Modulation		
Test	**Liquid Propellants**	P_{cham}	Φ	**Rate**	**D.C.**	**Mass**	Δp	Δp **w/Torch**	Δp **w/GOX**
	[Vol. Frac.]	**[psig]**	**[ ]**	**[Hz]**	**[ ]**	**[g/Inj.]**	**[psi]**	**[psi]**	**[psi]**
6/25-03	100% H_2O	176	0.35	10	6.0%	0.08	17	40	
6/29-05	100% CH_3O	161	0.36	10	6.0%	0.09		58	95
9/14-08	25% CH_3NO_2 / 75% CH_3O	239	4.85	20	8.0%	0.05	5	0	11
9/17-12	50% CH_3NO_2 / 50% CH_3O	248	4.82	20	8.0%	0.05	21	0	9
9/23-05	75% CH_3NO_2 / 25% CH_3O	253	4.91	4	2.4%	0.10			30
10/01-07	100% CH_3NO_2	338	1.02	20	10.0%	0.09	28	31	40
10/01-12	100% CH_3NO_2	342	1.00	40	20.0%	0.07		40	130
10/05-06	90% CH_3NO_2 / 10% C_3H_6O	426	1.01	40	24.0%	0.09		18	150

rates, equivalence ratios, chamber pressures and so on were varied throughout the testing. An image from a typical hotfire test is shown below in Figure 5. Strong modulations in chamber pressure were not observed in testing with only pulsed monopropellant. Significant but still substantially less than ideal modulations were observed in the partially pulsed bipropellant testing of methanol, neat nitromethane and nitromethane blended with propylene oxide.

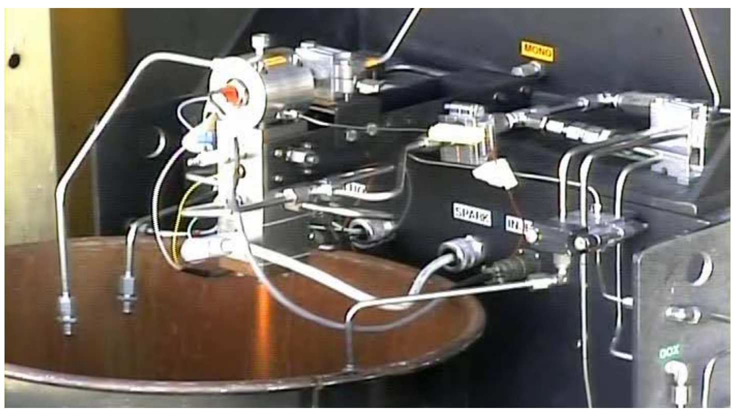


Figure 5. Image from a typical hotfire test.

Results from one of the more successful tests are presented below in more detail and compared to an ideal cycle model. The pressure history of test 10/01-12 is presented below in Figure 6. A near stoichiometric torch flow starts at 0 s and continues for approximately ½ s. The nitromethane then begins pulsing into the chamber and the hydrogen flow is terminated. Until the hydrogen in the feed lines and combustion chamber is depleted, little chamber pressure modulation is achieved, but the chamber pressure does rise in response to the increasing density in the combustion chamber. After the hydrogen is consumed, significant chamber pressure modulation is observed. However, comparison of the injector dynamic pressure trace shows that only every other injection pulse results in significant pressure modulation. The cause of this is unknown at this time. Such behavior has only been observed for injections occurring at frequencies greater than 20 Hz. This behavior may be due to interaction of the injector with the fluctuations in chamber pressure, resulting in strong fluctuations in mass delivered or atomization from shot to shot, or it may be due to resonance in the monopropellant feed system.

The numerical model which was described above has been used to predict the ideal performance of a pulsed combustor rocket motor under the test conditions described in Figure 6, using three different cycle models. The results are shown below in Figure 7. The gaseous propellant flowrates are reasonably well described by the conditions indicated in Figure 7. The liquid propellant flowrate used in the model is a representative flowrate from the experimental data, based on the mean chamber pressure taken from 0.75-0.80 s. The actual flowrate achieved during each injection pulse may differ substantially from this representative value, but the model should give a reasonable indication of the ideal behavior. The Steady model shows the ideal chamber pressure for the constant-pressure process which would be comparable to the test firing. Two pulsed combustion model results are also shown. The Instantaneous Injection model assumes that all of the mass added during each pulse is injected in the first instant of the injection. As shown, this process results in the very high transient pressures. The Distributed

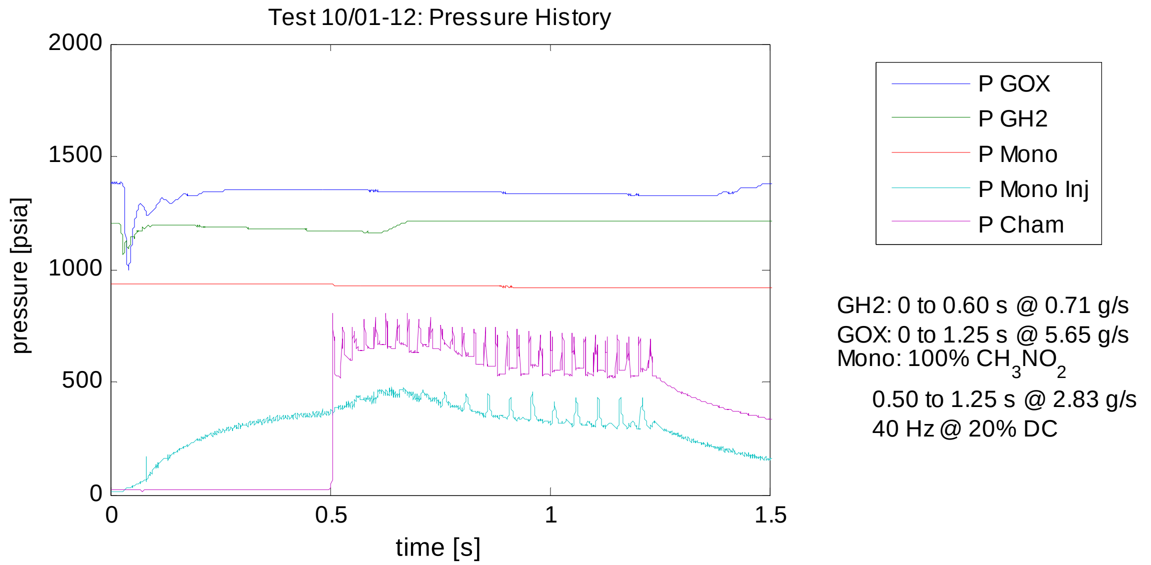


Figure 6. Pressure history of a partially pulsed GOX/ nitromethane test firing.

Injection model distributes the liquid propellant injection across the full injector duty-cycle used in the test (5 ms out of the 25 ms injection period in this case). Results from this cycle have much lower peak pressures than the instantaneous injection model, but still substantially higher peak pressures than those which occurred during the hotfire test. This model is meant to account for the finite nature of the propellant flowrates and should more realistically depict an attainable process. This model does not allow for the rapid fluctuations in instantaneous propellant flowrate that would actually occur during a dynamic injection. The instantaneous flowrate would actually rise as the poppet valve opened, briefly reach some quasi-steady flowrate, and then decrease as combustion ensued in the combustion chamber and raised the back pressure across the injector. The numerical model makes no attempt to account for time response of valves, pressure regulators, propellant transport, mixing or combustion and consequently responds much faster to changes in system condition than the actual system.

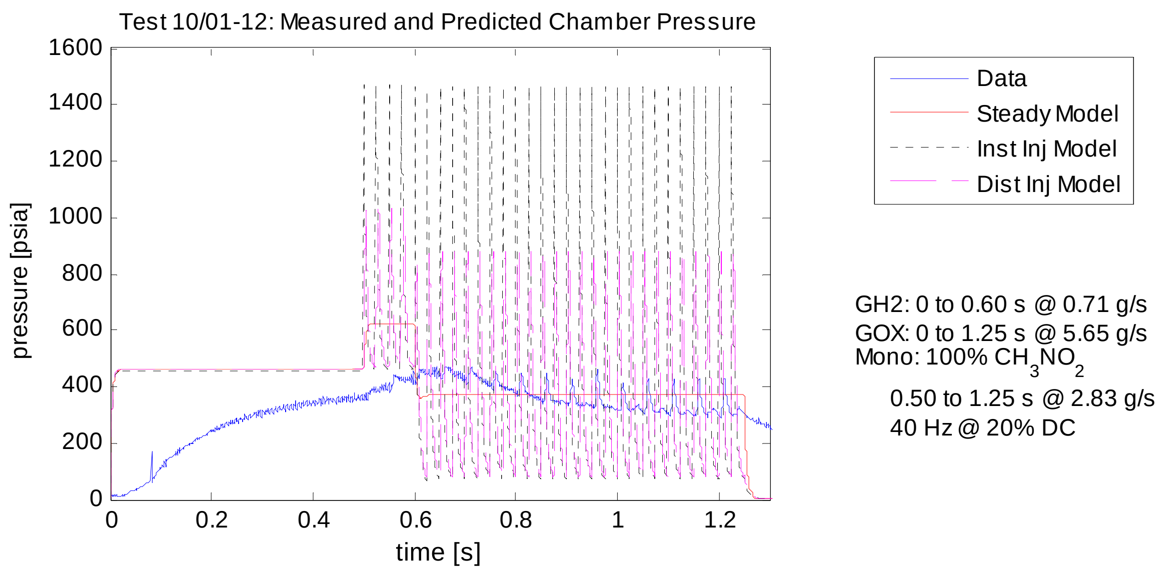


Figure 7. Comparison of the measured chamber pressure with results of numerical modeling.

A couple of observations can be made in comparing the models with the actual data. The gaseous propellant flows of the torch igniter do not achieve the ideal chamber pressure – which is the same constant pressure process in all three models. This less than ideal performance is expected due to the high rate of heat loss to the combustion chamber walls. Once the liquid propellant begins pulsing in, the measured chamber pressure most strongly resembles the steady flow model. This may be due to many causes but is likely due to poor atomization and substantial deposition of liquid propellant on the combustion chamber walls. That propellant is then vaporized back into the chamber flow at a slower rate and reacts with the available oxygen. Consequently the pulsed combustion is largely damped out into a near constant pressure process. The chamber pressure excursions which do occur are likely due to combustion of the finely atomized portion of the liquid propellant which reacts with the oxygen available in the chamber at that time. This cycle does not achieve the low chamber pressure at the end of the combustion cycle which will be required to achieve significant operational benefits over the comparable constant pressure cycle.

No parametric studies of pulsed combustor performance have been performed yet, but a number of observations have been noted. The amount of pressure modulation that is achieved increases with both the igniter torch pressure, and the amount of liquid propellant flow. Both of these conditions produce a higher average chamber pressure, which tends to increase the reaction rate of the fuel and possibly improve atomization. Nitromethane and nitromethane mixtures have proven difficult to ignite as a monopropellant at low pressure in this facility and sustained pulsed operation was not achieved. Additional work with a more volatile monopropellant might better facilitate a more operable cycle.

SUMMARY AND CONCLUSIONS

A novel facility for exploring the feasibility of a constant-volume pulsed rocket combustor has been constructed and some initial testing has been performed. Results with monopropellant pulsed combustion have been unsatisfactory to this point, but some significant pressure modulation has been achieved in a partially pulsed bipropellant system. Further exploration of this concept will require additional development on the injector hardware to ensure better atomization. Nitromethane has not exhibited good ignition characteristics in these tests and a more volatile monopropellant would also increase chances for success. Further development of an accurate time-resolved mass flow measurement system will be necessary to fully resolve the operating conditions actually being achieved.

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